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ROCKET MEASUREMENT OF THE SECONDARY

ELECTRON SPECTRUM IN AN AURORA

by

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ABSTRACT

The differential flux of secondary electrons with energy greater than 6 eV was measured in a steady IBC I$^+$ aurora with an electron spectrometer aboard an Aerobee rocket. Except for the absence of structure in the energy range 10-20 eV, the observed spectrum is in excellent agreement with a recent theoretical prediction. About one-half of the observed N_2^+ emission at 3914 A can be accounted for by secondary electron excitation.

I. INTRODUCTION

Excitation by secondary electrons produced by the primary ioniz-
ing flux is the source of many of the observed optical emission features
of the aurora. Although our theoretical understanding of the role of sec-
ondary electrons in an aurora is fairly complete, there is surprisingly
little in the way of quantitative measurements to test the theoretical pic-
ture. We report here the results of a measurement of the differential
secondary electron flux made in a rocket payload which also included
visible and ultraviolet photometers and an ion mass spectrometer. Ex-
cept for the absence of structure in the energy range 10-20 eV, the ob-
served secondary electron spectrum is in excellent agreement with the
recent theoretical predictions of Rees, Stewart, and Walker (1969), and
is found to be independent of altitude. About one-half of the observed
emission of the N_2^+ first negative band at 3914 A can be accounted for
by secondary electron excitation. The remainder is most probably due
to excitation by the primary auroral electrons, which were not measured
in this experiment.

II. THE EXPERIMENT

The secondary electron spectrometer was a 180° spherical elec-
trostatic deflection type analyzer. A complete description of the analyzer
and the calibration procedure has been given by Doering et al. (1970).
The geometric acceptance angle of the analyzer was a fan-shaped beam,
$8^{\circ} \times 120^{\circ}$, with the larger angle oriented parallel to the symmetry axis
of the rocket. The spectrum was scanned at a nominal 15 Hz rate by an

exponentially decaying sawtooth voltage which varied between 800 volts and 5 volts. The resolution, $\Delta E/E$, was constant at 2.5% over the entire energy range.

Of the other instruments on the payload, only the filter photometer provided data relevant to the analysis of the secondary electron spectrum. This unit consisted of three independent interference filters-- photomultiplier units sighted along the spin axis of the rocket. The three filters included the OI auroral green line at 5577 A, the (0,0) band of the N_2^+ first negative system at 3914 A, and the (5,2) band of the N_2 first positive system at 6685 A.

The instruments were carried aboard an Aerobee 150 rocket (NASA 4.217 UA), launched from Ft. Churchill, Manitoba, at 2241 CST on February 8, 1968. A bright auroral form was present overhead at the time of launch but quickly faded to the extent that the 5577 A photometer indicated somewhat less than 2 kR as the rocket entered the aurora (IBC I$^+$). The aurora was very steady except for a momentary fluctuation on the upleg of the flight (Parkinson et al., 1970a). A peak altitude of 154.87 km was reached 213 seconds after launch. The results of the other experiments have been discussed by Opal et al. (1970), Donahue et al. (1970), Parkinson et al. (1970b), and Dick and Fastie (1969).

III. THE SECONDARY ELECTRON SPECTRUM

Approximately one second of the telemetry record is reproduced in Figure 1. The upper trace shows the voltage sweep applied to the
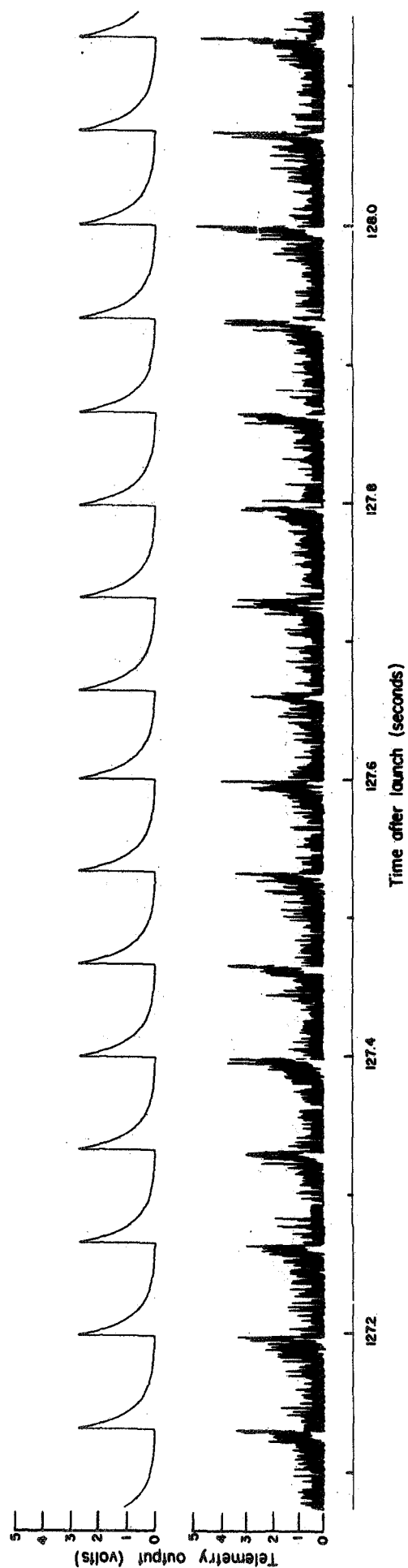
Fig. 1. A sample of the telemetry record showing the spectrometer sweep voltage (upper trace) and the output from the electron multiplier (lower trace).

ungrounded sphere of the electron spectrometer. The sweep rate is

15 Hz and the electron energy (proportional to the telemetry voltage

on this channel) exponentially decreases from 800 eV to 6 eV with a

time constant of 14 milliseconds. The lower trace shows the output

from the electron multiplier. Note the increase in signal as the elec-

tron energy decreases with time during each sweep. The increase of

the low energy electron flux in the sweeps near the end of the segment

shown in Figure 1 corresponds to the auroral pulsation reported by

Parkinson et al. (1970a).

Pulses corresponding to single electrons reaching the entrance

of the electron multiplier are clearly discernible on the record during

the high energy portion of each sweep. Only a few of these pulses are

"dark" counts. The majority are photoelectrons produced at the first

dynode of the electron multiplier by auroral ultraviolet photons scattered

from the interior surfaces of the electron spectrometer. This back-

ground is found to be completely independent of energy in a given sweep

but does follow the auroral intensity with time. Failure to properly ac-

count for this background can lead to an erroneous interpretation of the

secondary electron spectrum, as will be illustrated below.

Since the aurora was quite weak, the electron counting rates were

low, and in order to obtain statistically significant spectral information,

a large number of sweeps had to be summed. The data were digitized at

a rate of 5 kHz, separated into individual sweeps, and then summed 90

at a time, for an average over 6 seconds. A typical summation is shown
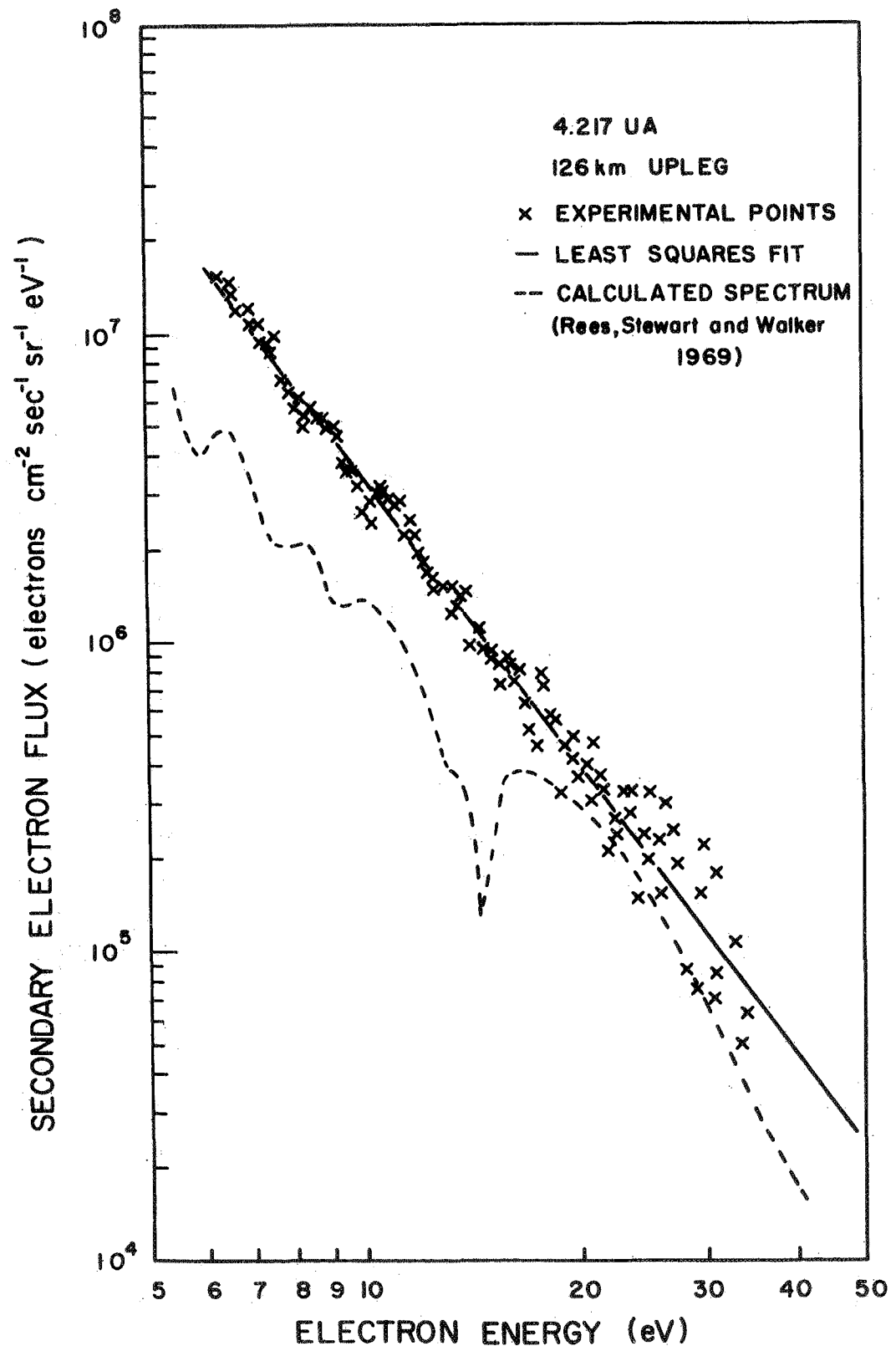
Fig. 2. A typical secondary electron spectrum obtained by summing 90 individual spectrometer sweeps. The summation over 6 seconds in time corresponds to an average over 4.5 km of altitude. The dashed curve is the calculated spectrum of Rees et al. (1969).

in Figure 2, after subtraction of background signal and conversion to electron flux per unit energy interval. In a day airglow experiment containing an identical electron spectrometer (Doering et al., 1970) the excitation rate of the N_2 second positive system calculated from the measured photoelectron flux was found to agree with the observed (0, 0) band emission at 3371 A to within 30%, so that we may adopt this figure as the uncertainty in the absolute value of the secondary electron flux. There is, however, some uncertainty in the electron energy due to the possibility of a vehicle potential (typically ~ -1 volt) which was not measured in the present experiment.

Each 6-second summation of 90 spectrometer sweeps was fit by a least-squares procedure to a power-law spectrum of the form

$$F (E) = F (E_o) (E/E_o)^\alpha \qquad (1)$$

Here F (E) is the secondary electron flux in electrons $cm^{-2} sec^{-1} sr^{-1} eV^{-1}$ at energy E. Both $F (E_o)$ and the "spectral index" α are determined from the least-squares fit. The solid line in Figure 2 shows that the fit is quite good. In Figure 3, we plot both the spectral index α and the logarithm of $F (E_o)$, for $E_o = 10$ eV, as a function of time and altitude. Except for the outburst on the upleg noted above and a slight increase after apogee, the magnitude of the secondary electron flux appears to be fairly constant in time and altitude within the aurora. The lower border of the aurora, in terms of the secondary electrons, is at ~ 100 km. The spec-
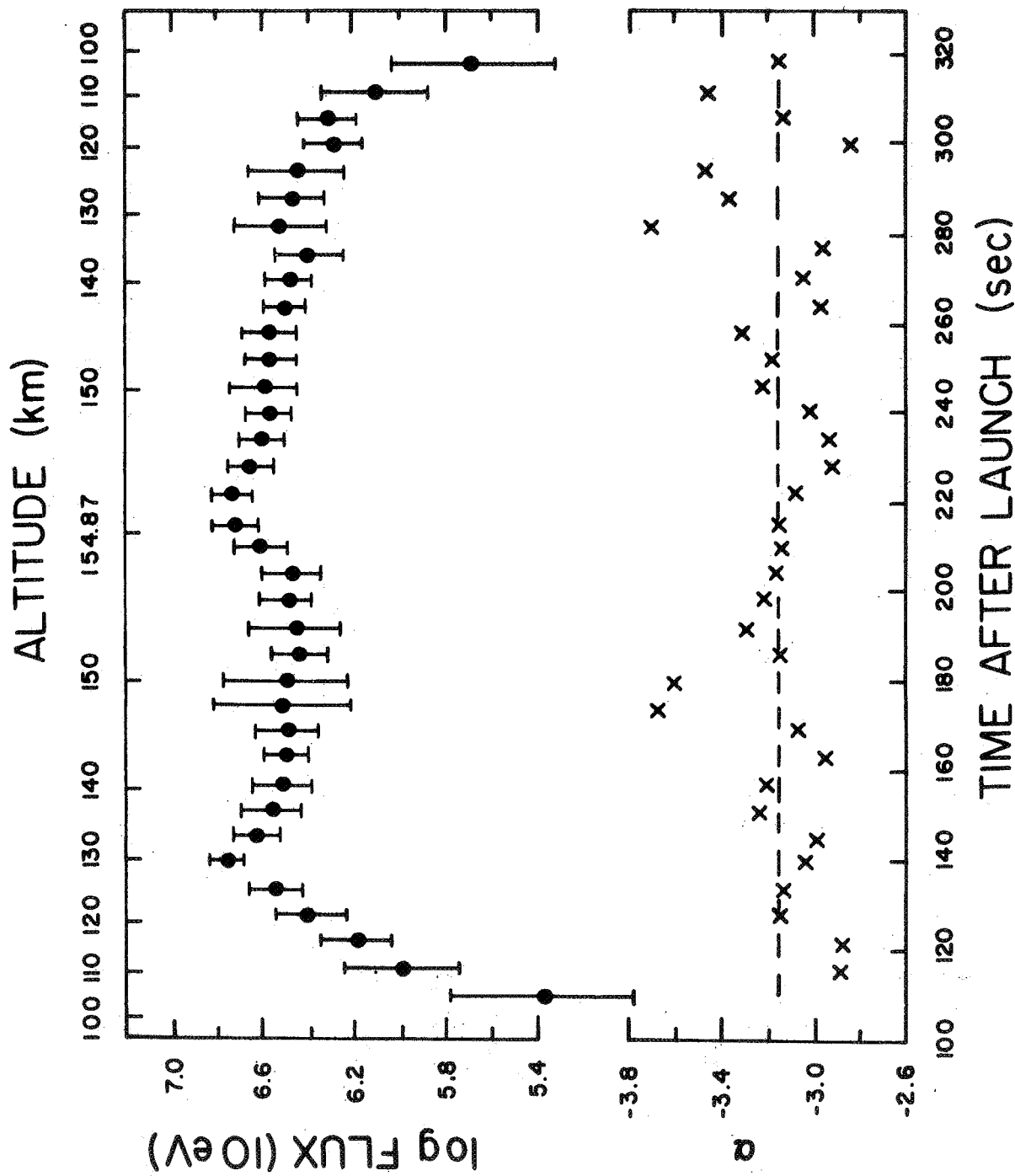
Fig. 3. The logarithm of the secondary electron flux at 10 eV (in electrons cm^{-2} sec^{-1} sr^{-1} eV^{-1}) and the spectral index, α, for 6-second summations of the data as determined by the least-squares fit, are shown as a function of both time and altitude. The dashed line represents the mean value of α = -3.17 ± 0.04.

tral index α was found to be completely independent of time and altitude.
It has an average value = -3.17 ± 0.04, as indicated by the dashed line
in Figure 3. It is amusing to note that, to within the statistical uncer-
tainty, $-\alpha = \pi$.

Because of the low counting rates noted above, only data for elec-
tron energies less than 30 eV were used in fitting the data to a power-law
spectrum. In order to extend the statistical significance of the data out
to 50 eV, we took summations over 36-second intervals, corresponding
to 540 individual sweeps. The results are shown in Figure 4, which
contains a spectral synopsis of the entire flight. The figure demonstrates
both the constancy of the spectral index and the validity of the power-law
spectrum out to 50 eV.

IV. COMPARISON WITH THEORY

In Figure 2 we reproduce the calculated spectrum of secondary
electrons of Rees, Stewart, and Walker (1969). Although their calcula-
tion was specifically intended to correlate with measurements at 105 km
made during a different aurora, their analysis shows that the spectrum
of secondary electrons is almost independent of the energy of the primary
electrons and varies only slightly with altitude as the chemical composi-
tion of the upper atmosphere gradually changes. The secondary flux, of
course, depends on the primary flux, but for purposes of clarity, we
have not normalized the calculated value of the secondary flux to our data.
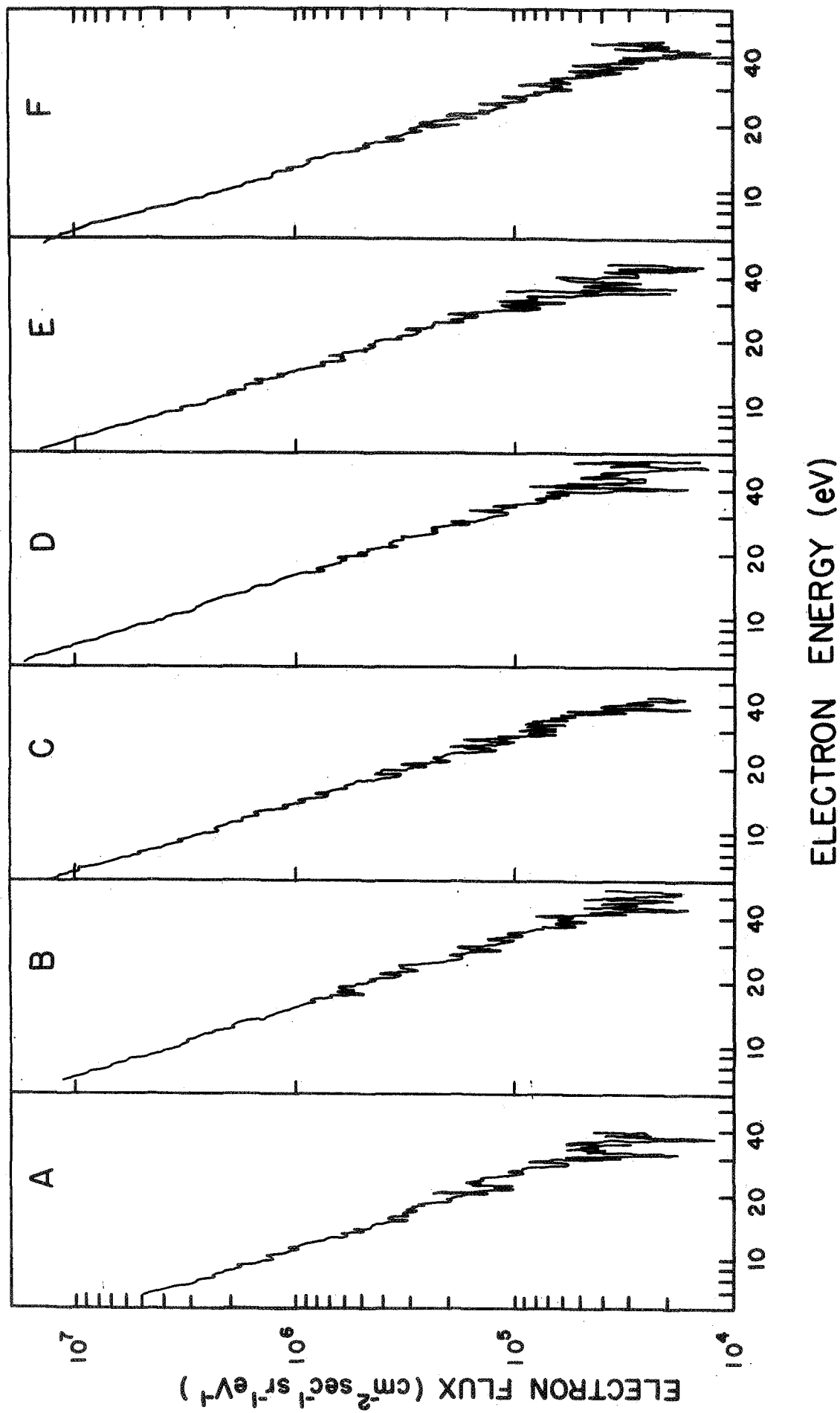Except for the absence of the predicted structure between 10 and 20 eV

Fig. 4. Secondary electron spectra obtained by summing 540 individual sweeps, or approximately 36 seconds. The altitude range is A, 95-127 km; B, 127-147km; C, 147-155 km; D, 150-155 km (downleg); E, 133-150 km; and F, 105-133 km.

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due to electron excitation of the N_2 second positive bands, the observed

spectrum very closely resembles the calculated spectrum. For energies

between 40 and 100 eV, where our observed flux is lost in the noise, the

calculated spectrum continues to decrease with the same power law

behavior.

The absence of structure in the spectrum may be instrumental,

resulting from the summation of points that do not correspond to exactly

the same energy. However, an analysis of the energy spread introduced

by the "jitter" in the summations indicates that it is no worse than the

resolution, ΔE, of the spectrometer. At an energy of 15 eV, the resolu-

tion is ≈ 0.4 eV, certainly not large enough to smear out the pronounced

dip expected. The other possibility is that the spectrum is actually

washed out by an ionospheric electric field aligned along the geomagnetic

field lines. We only require that an electron lose or gain 1-2 eV in a

mean-free path, so that a field of the order of $10^{-3} V\ m^{-1}$ would be suf-

ficient to produce this effect.

There is little else in the literature to provide direct comparison

with our results. Ulwick (1968) derived a secondary electron spectrum

from measurements of the integrated flux (i.e., the total flux of elec-

trons with energy greater than some given value) up to an energy of 100

eV. Heikkila and Matthews (1964) measured electron energy distributions

with a low resolution detector which sampled a number of fixed energy

ranges between 30 eV and 2 keV in succession. Both of these experiments

give a power-law spectrum for energies less than 100 eV, with a spec-
tral index of $\approx$ -2.5. A previous measurement by Doering (quoted by
Pfister, 1967) gave a spectral index of -1.35, but this result is now known
to be incorrect since no account was taken of the ultraviolet photoelectron
background.

V. OPTICAL EMISSION FEATURES

We turn next to an examination of the correlation that exists be-
tween the measured secondary electron flux and the auroral optical emis-
sions. Ideally, one would expect the best correlation to be obtained for
the N_2 first or second positive group emissions, since excitation to the
$B^3\Pi_g$ and $C^3\Pi_u$ states from the ground $X^1\Sigma_g^+$ state is possible only by
electron impact. The cross sections peak only a few eV above the thres-
hold energy (7.35 eV and 11.05 eV, respectively) and then fall off rapidly
so that excitation by primary electrons is negligible. Furthermore, the
emissions $(B^3\Pi_g \rightarrow A^3\Sigma_u^+$ and $C^3\Pi_u \rightarrow B^3\Pi_g)$ are fully allowed and not
subject to collisional quenching at auroral altitudes. Unfortunately, the
data from the photometer covering the (5, 2) band of the N_2 1PG at 6685 A
were contaminated with scattered moonlight during the major part of
each rocket precession period, so that detailed altitude profiles could
not be obtained. The data yield information about the ratio of the integ-
rated intensities of 6685 A and 3914 A which we will discuss later.

Electron excitation of the (0, 0) band of the N_2^+ first positive sys-
tem at 3914 A has been studied extensively in the laboratory (e. g.,

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Borst and Zipf, 1970; Holland, 1967). The cross section rises gradually
from a threshold at 18.8 eV to a peak near 100 eV and then gradually de-
creases. At 1 keV the cross section is still large enough to account for
a significant contribution to 3914 A emission from excitation by primary
electrons. The data from the 3914 A photometer were not contaminated
by moonlight and since the aurora was fairly steady, it was possible to
determine an apparent volume emission rate by differentiating the ob-
served intensity from an overhead column with respect to altitude. This
is shown by the solid line in Figure 5 for the upleg of the flight, and Fig-
ure 6 for the downleg.

Assuming that the power-law spectrum with the same spectral
index is valid for secondary electrons with energies greater than 50 eV
and that the distribution of secondary electrons is isotropic at all altitudes,
the 3914 A volume emission rate due to secondary electrons was calcu-
lated from

$$I_s(z) = 4\pi n(z) \int_{E_{th}}^{\infty} F(E, z) \, \sigma(E) \, dE, \tag{2}$$

where $F(E, z)$, the flux of secondary electrons in electrons $cm^{-2} sec^{-1}$
$sr^{-1} eV^{-1}$ at energy E and altitude z is given by Equation (1), $\sigma(E)$ is the
optical cross section, and $n(z)$ is the number density of nitrogen mole-
cules at altitude z. A model atmosphere from the U. S. Standard Atmo-
sphere Supplements, 1966 was chosen to best fit the time of year, geo-
graphic latitude and exospheric temperature at the time of the flight.
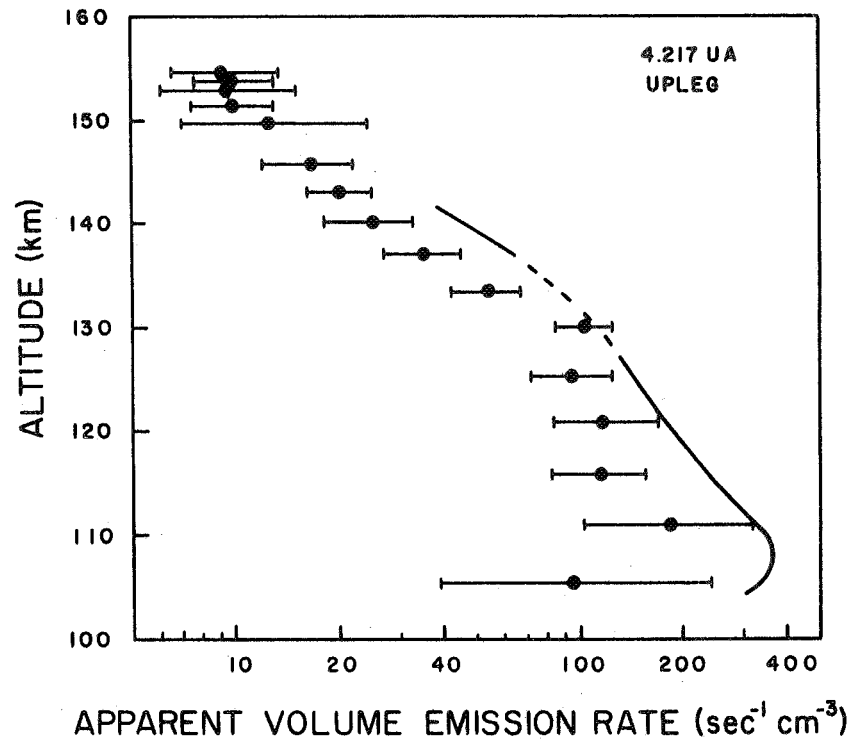The calculated volume emission rates and the uncertainties due to the

Fig. 5. Calculated and observed volume emission rates for the (0, 0) first negative band of N_2^+ at 3914 A on the upleg of the flight. The solid line is the observation. The dashed part of the curve is where the momentary enhancement was subtracted to obtain the smooth altitude profile.
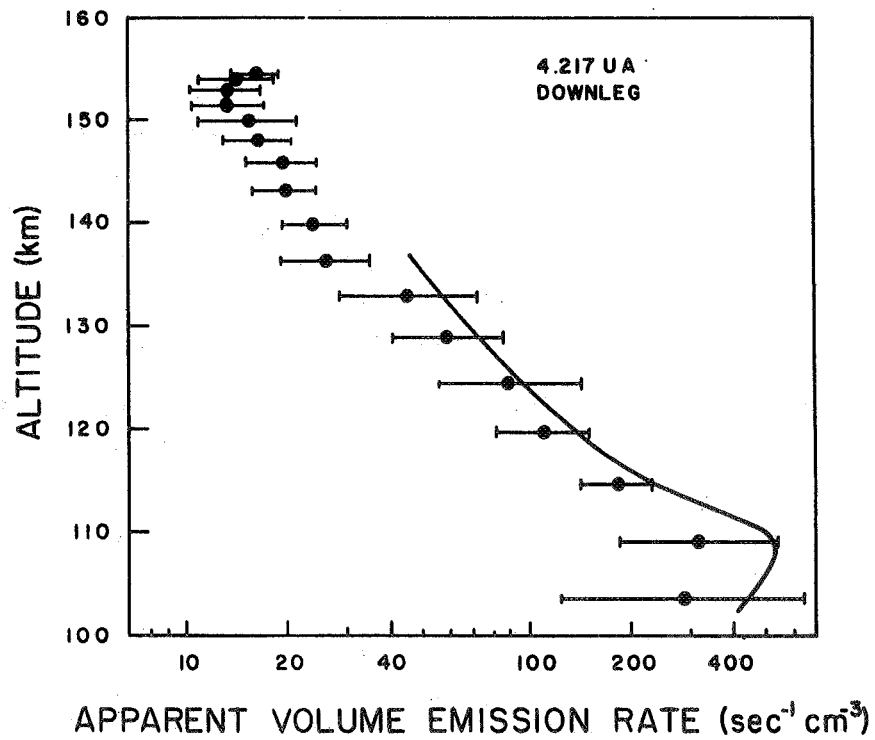

Fig. 6. Calculated and observed 3914 A volume emission rates for the downleg of the flight.

statistical uncertainty in the electron flux are also shown in Figures 5 and 6. In both cases the calculated emission rates are lower than the observed ones--by a factor of two on the upleg and about 50% less on the downleg. This difference may be real or may result from the uncertainties in the absolute flux calibration, a difference between the actual atmospheric densities and the model used in the calculations, or an erroneously derived volume emission rate due to temporal changes in brightness of the 3914 A emission. The contaminated 6685 A data is sufficient to prove that the difference is, in fact, real.

During a precession period of the rocket, the angle between the look direction of the photometer and the moon varies in a periodic manner, so that the scattered moonlight is a minimum when this angle is greatest. Near apogee, the minimum scattered light signal from the 6685 A photometer is less than the dark current, so that it is fair to assume that at lower altitudes the observed 6685 A intensity at points of maximum photometer-moon angle will be the true 6685 A emission. These occur at 88 km on upleg and 90 km on downleg. At these two points we have evaluated the ratio of the 6685 A intensity to the 3914 A intensity, which we find to be 1.66 and 1.88, respectively.

At any altitude, the ratio of the volume emission rates of these two bands can easily be calculated from

$$\frac{I_{6685}(z)}{I_{3914}(z)} = \frac{\int F(z, E) \, \sigma_{6685}(E) \, dE}{\int F(z, E) \, \sigma_{3914}(E) \, dE} . \qquad (3)$$

The subscript notation is self-explanatory. In terms of Equation (1), this becomes

$$\frac{I_{6685}(z)}{I_{3914}(z)} = \frac{\int E^{\alpha} \cdot \sigma_{6685}(E)\, dE}{\int E^{\alpha} \cdot \sigma_{3914}(E)\, dE} . \tag{4}$$

If the spectral index is independent of altitude, the ratio of the integrated column intensities will also be given by Equation (4). In evaluating this ratio, we used the energy dependence of the first positive cross section, which includes cascade from the second positive system, given by Stanton and St. John (1969) and the absolute cross section value given by Shemansky and Broadfoot (1970). The calculated ratio, 4.07, is larger than that observed on both legs of the flight, and implies that about one-half to two-thirds of the observed 3914 A column emission is due to excitation by primary electrons. Near the lower edge of the aurora the spectrum of primary electrons changes rapidly (Rees, 1969) and we expect that the fraction of 3914 A emission produced by the primaries is not constant with altitude. We note that the change in intensity ratio of LBH to 3914 A observed by Opal et al. (1970) on the same flight at the lower edge of the aurora may reflect such a change in the relative contribution to the excitation of 3914 A by the primary and secondary electrons.

Finally, we wish to comment on the analysis of auroral green line data by Parkinson et al. (1970 b). In calculating the contribution due to direct electron excitation of oxygen atoms, they used the 1967 data of Doering which, without the subtraction of the photoelectron background, gave a spectral index of -1.35. However, this spectrum overestimated

the 3914 A intensity by a factor of 6 and hence they accordingly assumed

the absolute calibration of the secondary spectrometer to be in error by

this factor. As a result, they underestimate the contribution of direct

excitation by secondary electrons. While this does not affect their con-

clusion that direct excitation plus dissociative recombination are insif-

ficient to account for the observed 5577 A emission, it does alter signi-

ficantly their estimate of the requisite cross section for the proposed

dissociative excitation mechanism. Rees et al. (1969) reach the same

conclusion regarding the 5577 A emission on the basis of their calculated

spectrum.

ACKNOWLEDGEMENTS

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